The influence of non-equilibrium dust formations on the atmosphere of brown dwarfs

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Abstract

Available dust models often assume phase–equilibrium for dust formation to deliver the depletion of gas phase elements which form condensed matter. These models are successfully used to provide opacities in radiative transfer codes (e.g. Allard et al. 2001; Burrows et al. 2002; Marley et al. 2002; Tsuji 2002).
More detailed, self–consistent modeling of the quasi–static dust problem using a kinetic approach assumes equilibrium chemistry and considers nucleation of TiO2 seed particles, a dirty growth and gravitational drift of the particles (Woitke & Helling 2003, 2004). Nevertheless, the feedback on atmospheric structures could not been taken into account until now:
The problem of coupling the dust formation and its impact on the radiation field is iteratively being solved using the classic stellar atmosphere code PHOENIX (Hauschild & Baron 1999) by solving the frequency dependent radiative transfer and the structure of the atmosphere in hydrostatic equilibrium. The dust model by Woitke & Helling (2003, 2004) and Helling & Woitke (2006) for oxygen–rich dwarfs needs an atmospheric structure and provides properties of the dust clouds, which, in turn, allows to calculate dust opacities as input for the radiative transfer problem.
We demonstrate recent progress of modeling late–type stars of spectral type L having effective temperatures of 1800...2400 K. We discuss the change of spectral appearance and the change of 2MASS-colors J–K with varying column density of the dust.

Method

- PHOENIX delivers atmosphere structure in order to solve dust problem first
- 43 elements and reduced set of molecular species of 22 (CPU–time) in the PHOENIX-part
- For good spatially resolution, number of atmosphere layers is set to 256

Treatment of dust

- Temperature T, gas pressure P_{gas}, density ρ, convective speed v_{conv}, depth z, mean molecular mass μ, and element abundances ϵ are handed to the DRIFT
- DRIFT routine solves the dust momenta equations
- Yielding L_j, defined by

$$\rho L_j = \int_{V_l}^{\infty} f(V) V^{j/3} dV \text{ with } j = 0, 1, 2, ...$$

- $f(V)$ a priori unknown grain distribution in volume space
- V_l the minimal dust volume, arbitrary set to $1000 \times V(\mathrm{TiO_2})$
- ρL_j also contain information of dust mean grain size $\bar{a}$ and particle number of dust N_{dust}
- Fractional dust composition, nucleation rate J^*, and netto dust growth χ_{net} are also calculated

Grain size distribution

- Grain size distribution is a priori unknown
- First guess for estimating broadness of distribution:

$$f(a) = \sum_{i=1}^{2} N_i \delta(a - a_i)$$

- N_i and a_i are unknown paramters, algebraically found with L_j, $j = 0 \ldots 3$

Opacities

- Layer dependent mean grain sizes, fractional compositions, and particle numbers
- Opacities are handed to radiation transfer part of PHOENIX
- Inhomogeneous dust grains $\rightarrow$ Optical properties calculated by effective medium theory (EMT, Bruggeman, 1935)
- EMT finds permeability of medium consisting of spherical inclusions in small particle limit
- Due to grain sizes, Mie theory is needed (Mie 1907, Bohren & Huffman 1983)

Adjusting the structure

- PHOENIX adjusts temperature structure with Unsöld-Lucy temperature correction
- Thus, we approach iteratively towards a consistent solution.

Models

- $T_{\mathrm{eff}} = 1800 \ldots 2400$ K
- $\log g = 5.0$
- Solar abundances (Anders & Grevesse, 1989).
- Models with $T_{\mathrm{eff}} < 1800$ K seem to have numerical instabilities; converge rarely
- Convection with mixing length theory, mixing length $l/H_p = 2$.
- For comparison, Cond and Dusty models (Allard et al., 2001) are calculated and their atmospheric structure used for calculating dust.

Results

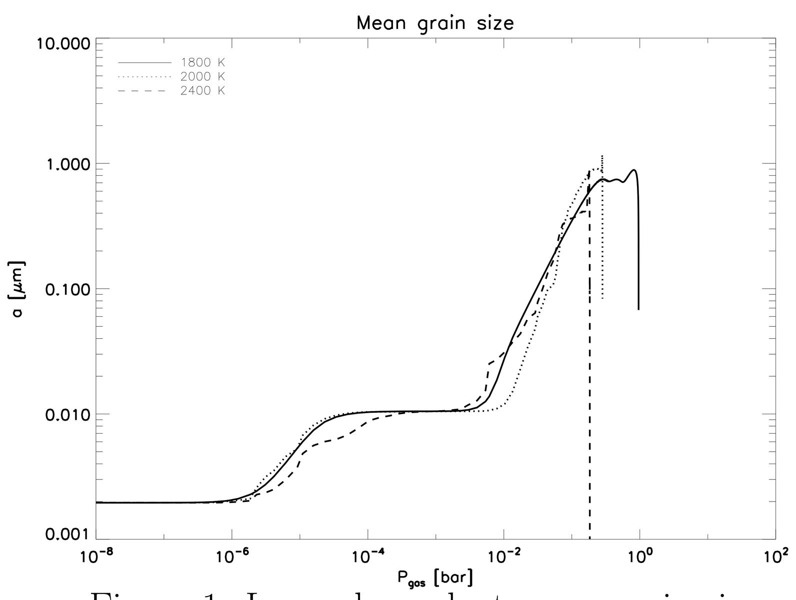

Figure 1: Layer dependent mean grain size

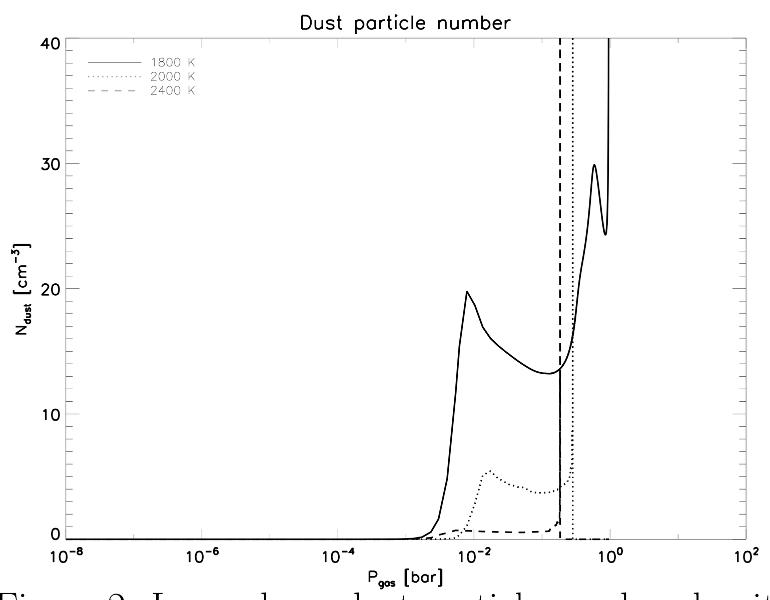

Figure 2: Layer dependent particle number density

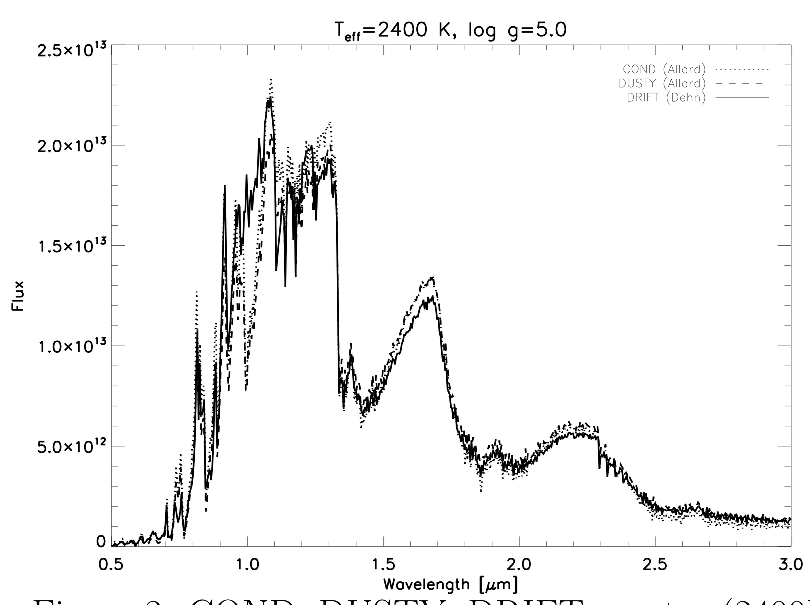

Figure 3: COND, DUSTY, DRIFT spectra (2400K)

The mean grain size of models with $T_{\mathrm{eff}} = 1800$, 2000 and 2400 K are quite independent of the effective temperature (figure 1), but the number density of dust (N_{dust}) increases with decreasing effective temperature (figure 2). So, N_{dust} is most responsible for dust opacities at these effective temperatures. The regions in the inner part of the atmosphere, where N_{dust} raises up to $100 \ldots 10^4$ cm^{-3}, have thicknesses of 1 cm to 200 m. Despite located in optical thin regions, their impact on the opacity might be weak, because the thickness of these regions becomes smaller with higher peaks of N_{dust}, so the column density of dust ($\int N_{\mathrm{dust}} dz$) keeps constant there.

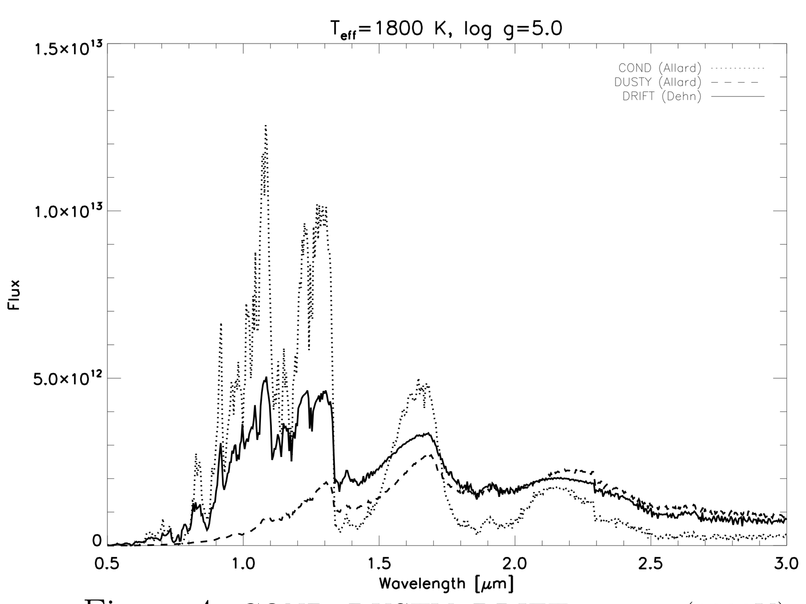

Figure 4: COND, DUSTY, DRIFT spectra (1800K)

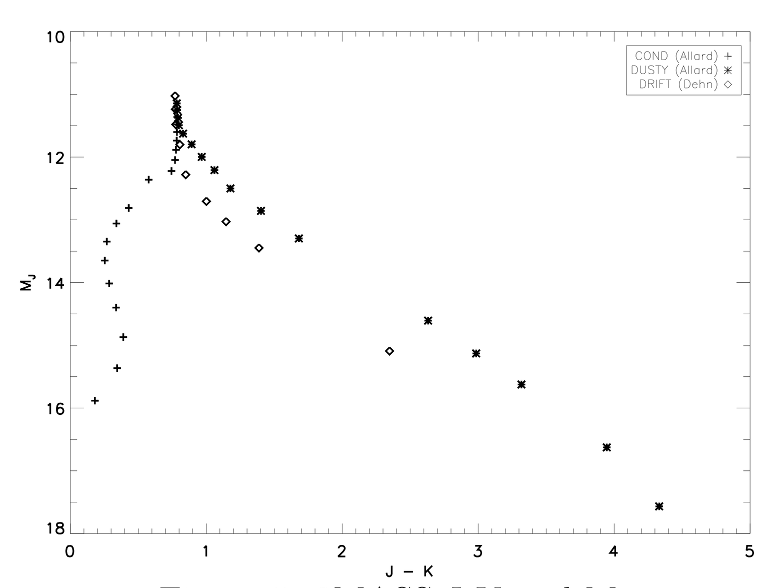
Figure 5: 2MASS J-K and M_J

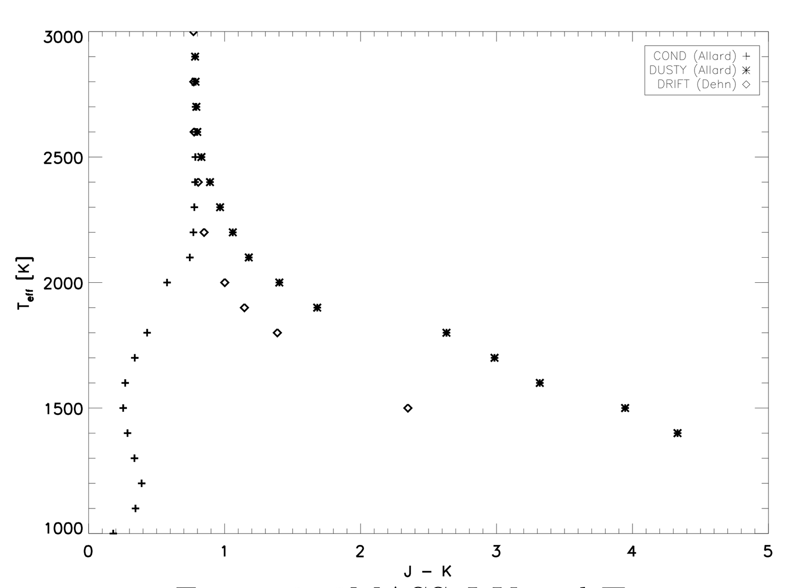
Figure 6: 2MASS J-K and T_{eff}

Modelled spectra with our dust model compared to COND and DUSTY model spectra by Allard et al. (2001) are shown in figures 3 and 4. The COND models assume the formation of dust which settles into optical deep part of the atmosphere and becomes invisible. DUSTY models assume dust formation, remaining in in the visible part of the atmosphere where it forms. In our models, the total column density of dust is about 10^7 cm^{-2} at $T_{\mathrm{eff}} = 2400$ K and raises to 10^8 cm^{-2} at $T_{\mathrm{eff}} = 1800$ K. Thus, spectral features of the different models are quite similar at $T_{\mathrm{eff}} = 2400$ K, but diverge significantly at $T_{\mathrm{eff}} = 1800$ K, especially in the J and H band. Our self consistent DRIFT models show 2MASS J-K color indices laying between the COND and DUSTY extremes, which is shown in the color-magnitude and color-temperature diagrams in figures 5 and 6.

Outlook

We presented self consistent dust models including their influence on the atmospheric structure. Some predictions concerning observable color indices in the near infrared are made. For future work, we are going to change surface gravity and metallicity of our models in order to explain variations of color index J-K of objects with the same spectral type L (e.g. shown in Tsuji 2002). Furthermore, we want to focus on lower effective temperatures (< 1500 K) covering the transition region from L to T dwarfs in order to reproduce the predicted presence of dust clouds in optical thick layers.

References

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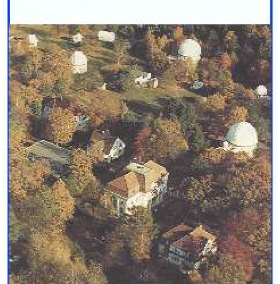

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